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Provision of Emission Control Area and the impact on shipping route choice and ship emissions

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ABSTRACT

This paper investigates the impacts of Emission Control Areas (ECAs) on aspects of global shipping. As the direction and degree of climate change have become increasingly well documented, emissions from ships have received more attention from the shipping industry. By using data for the Asia–Europe route, we model the route-choosing behaviour of liner shipping though possible ECA in the Mediterranean Sea. Our investigation reveals that, if an ECA is established, a considerable portion of ships will re-route around the ECA and regional emissions will be excessive under certain conditions. Small ships are more inclined to re-route than big ships. Therefore, despite the potential reduction of ship emissions in one area, our findings suggest that more internationally coordinating effort should be directed towards reducing ship emissions.

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1. Introduction

The IMO (International Maritime Organization) have established measures on different issues. Current maritime emission regulations set limits for SO_x and NO_x for health and environmental reasons, and for CO_2 to mitigate global warming (Eide et al., 2013; Lindstad and Sandaas, 2014; Lindstad et al., 2015). One of IMO established measures is ECAs (Emission Control Areas). ECAs were first defined in Annex VI of the 1997 MARPOL (International Convention for the Prevention of Pollution from Ships) protocol, and came into effect in 2005. Emission requirements are much stricter in ECAs compared with outside such areas. Up to now, ECAs designated under MARPOL Annex VI for SO_x and particulate matter emission control include the Baltic Sea area, the North Sea area, the North American area and the Unites States Caribbean sea area. Among these ECAs, the North American area and the Unites States Caribbean sea area are also ECAs established for NO_x emission control (IMO, 2016). As regulators are determined to control ship emissions around populated cities, other areas are being considered to be added via the MARPOL protocol. Recently, the possible designation of the Mediterranean Sea as ECAs has been discussed (Panagakos et al., 2014).

It is confident that an ECA imposes limits on emissions which will definitely yield a reduction in emissions within the ECA. It will be beneficial if more quantitative analysis can be conducted on designating a new ECA by evaluating the ship emission reductions. Some previous studies have focused on regional ship emission reductions by ECAs: Poplawski et al. (2011) calculated ship emissions in Victoria, Canada; Schemban et al. (2012) investigated the influence of ship emissions

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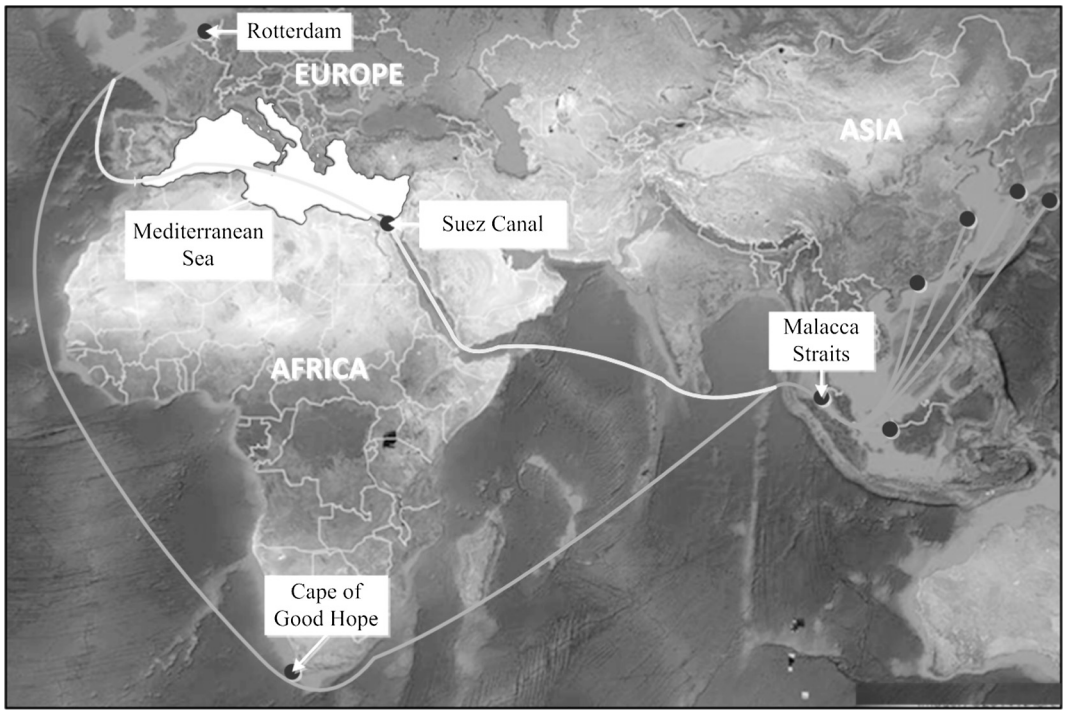

Fig. 1. Asia-Europe shipping routes.

on air quality in Mediterranean Sea harbours; and Chang et al. (2014) assessed the noxious gases of vessel operations in a potential ECA; Svindland (in press) presented SO_2 emission calculations of two container feeder vessels in a pre- and post ECA regulation setting. Those studies investigated the impact of ECAs by analysing changes (reductions) in shipping emissions. However, those studies focused on local harbours and ignored the influence of ship route change. With the establishment of new ECAs, ships' routing will change in response, and hence emission reductions should be adjusted according to the changes in ships' behaviour. Fagerholt et al. (2015) performed a computational study on shipping routes to evaluate possible impacts on sailing paths and speeds from the ECA regulations. The study showed that ship operators will often choose to sail longer distances to avoid sailing within ECAs. Therefore, it is important to conduct more studies on the shipping route configuration and associated implications under various ECA settings.

In 2014, the ECA Regulation Surcharge was implemented to the North American ECAs in the fixed amount per TEU. Although the ECA Regulation Surcharge is monitored and adjusted on a quarterly basis, the impact of this Surcharge has not been studied in the literature.

Seaborne trade between East Asia and Northern Europe can be made via the shipping routes via the Mediterranean Sea and the alternative via the Cape of Good Hope (Fig. 1). The establishment of ECAs means that all ocean-going vessels, if not using alternative fuels (methane, LNG, etc.) and/or abatement technologies, entering such areas would have to switch to low-sulphur fuel or pay an emission penalty. If emission standards in the Mediterranean Sea were to be controlled, the routes for shipping would likely be different. Currently, ships trading in designated ECAs have to use fuel oil on board with a sulphur content of no more than 0.10% from 1 January 2015, against the limit of 1.00% in effect up until 31 December 2014 (IMO, 2014).

Therefore, in the present study, we aims to contribute to ECA policy by modelling the possible effects of establishing an ECA in the Mediterranean Sea, with a focus on shipping route configuration and associated ship emissions along shipping routes. In Section 2 of the paper, we examine the literature on ship emissions, particularly those studies that have taken a modelling approach, and including with respect to ECAs. In Section 3 of the paper, we apply the Discrete Choice Model (DCM) to model the shipping route choice, including the process of setting modelling parameters. In Section 4, we present the results regarding route choice and corresponding emission reductions. Section 5 concludes the paper.

2. Literature review

The literature investigating ship emissions has focused on individual ships' emissions and the relationship of individual ships to the environment. Psaraftis and Kontovas (2010) studied various maritime policies on greenhouse gas emissions and discussed the ways of using reductions in steaming speed, changes in the number of ships in the fleet, and the use of in-

transit inventory holdings to address environmental protection needs. As slow steaming lengthens the voyage, Cariou (2011) raised the issue of whether slow steaming is a sustainable strategy of reducing CO_2 emissions. He estimated the emissions in various trade lanes to evaluate whether this strategy is sustainable in the long run, and showed that the speed reduction strategy could be achieved only within certain bunker price ranges for the major trade lanes. Lindstad et al. (2013) analysed the effects of speed reduction on direct emissions with respect to sea conditions and freight market conditions. The results of the analysis supported speed reduction initiatives as a method of reducing CO_2 emissions. The study found that emissions from a single ship can be reduced by 30% from 10.7 kg CO_2 per thousand ton per nautical mile to 7.4 kg CO_2 per thousand ton per nautical mile by lowering the vessel design speed by 20%. Woo and Moon (2014) tested whether slow steaming can reduce operating costs and CO_2 emissions at the same time. Those authors built a simulation model and found that within the typical speed range of 14–22 knots, a speed of 17.4 knots is optimal. Other studies of slow steaming and ship emissions include those of Eefsen and Cerup-Simonsen (2010), Kontovas and Psaraftis (2011), and Lindstad et al. (2011, 2012). Psaraftis and Kontovas (2013) presented a review paper of speed models in maritime transportation, including both non-emission and emission speed models. Psaraftis and Kontovas (2015) provided a good overview of the decision models for slow steaming in maritime transport.

The recent literature has been extended to include the carbon footprint of shipping and estimations of carbon emissions in the shipping and maritime industry. Leonardi and Browne (2010) proposed a method of calculating the carbon footprint of maritime transport of average ship sizes for mainstream routes of liner shipping. Miola and Ciuffo (2011) developed a model to estimate ship emissions as an element of the carbon footprint. Gibbs et al. (2014) analysed the carbon footprint of international shipping and investigated the role of sea ports in reducing greenhouse gas emissions. Armstrong (2013) reviewed various low-carbon shipping and decarbonisation options for reducing the overall carbon footprint.

Recent studies have used a range of different factors in speed reduction optimization and modelling investigations. Using simulation-based stochastic approximation methods, Qi and Song (2012) investigated the problem of designing an optimal vessel schedule to minimize fuel consumption and carbon emissions taking into consideration uncertain port time and frequency requirements. The study showed that the fuel consumption and emissions of a ship per nautical mile are a quadratic convex function with respect to speed. Norlund and Gribkovskaia (2013) examined various speed optimization strategies with periodic vessel schedules. The modelling results showed that a 25% reduction in emissions and fuel cost can be achieved without any increase in fleet size.

The establishment of ECAs will contribute to ship behaviour within such areas, resulting in emission control. Recently, Cullinane and Bergqvist (2014) edited a special issue on the effects of ECAs on maritime transport. Doudnikoff and Lascoste (2014) analysed the difference between ship speeds inside and outside sulphur ECAs and whether the speed increase due to the slow steaming within ECAs might increase CO_2 emissions over the total voyage cycle. The study proposed a cost model by minimizing the combined effect of speeds both inside and outside the ECA. The model was further applied to examine Northern Europe services.

3. Methodology

The concept of the utility can be used to compare different routes of transport. Assuming a ship owner or operator maximises her utility, she will choose a route that gives her the highest value of utility based on the utilities of all choice alternatives. To simplify the discussion, we assume all the ship owners or operators are individual and independent. The Discrete Choice Model (DCM) is an economic model that has been used to describe, explain, and predict choices between two or more discrete alternatives. The DCM statistically relates the choice made by an individual person to the attributes of the person and the alternatives available to the person. The DCM has widely used to predict demand for planned transport systems, such as driver route choice (Peeta and Yu, 2005; Yu and Peeta, 2011), pedestrian route choice (Hoogendoorn and Bovy, 2002), and commuters' choice of mode for trips (Forinash and Koppelman, 1993). The DCM has also been used to analyse the route choice behaviour in multi-modal networks (Hoogendoorn-Lanser et al., 2005; Bovy and Fiorenzo-Catalano, 2007). With respect to waterborne transport, the DCM has often been applied to study sea route choice. Tavasszy et al. (2011) used the DCM to build a port and route choice model for the global transportation of freight by container ships. Qu and Meng (2012) applied the DCM to model ship route choice under the hypothesis of an extreme scenario of a blockade of the Straits of Malacca and Singapore. Those studies demonstrated that DCMs are capable of formulating the problem of ships' route choice.

In the DMC, the utility that a ship obtains from taking an action is termed the random utility (U). The probability of choosing an alternative is equal to the probability that the utility of that alternative is greater than the utilities of all other alternatives (Train, 2009). The utility that the ship obtains depends on the attributes of the ship and on the route choice, some of which are observed by the researcher and some of which are not. Accordingly, the utility of ship i in choosing route n is:

$$\begin{aligned} U_{ni} &= V_{ni} + \varepsilon_{ni} \\ V_{ni} &= \sum_{a} \lambda_a x_{ni}^a \end{aligned} \tag{1}$$

where

U_{ni} is the random utility of ship i in choosing route n;

V_{ni} is the observable part of U_{ni};
ε_{ni} is the unobservable part of U_{ni};
x_{ni}^{a} is the a-th observed factor; and
λ_a is the corresponding coefficient for x_{ni}^{a}.

The distribution of ε classifies the DCM into different types: logit, probit, and mixed logit. The logit model is by far the most widely used type of DCM, and is derived under the assumption that the unobservable terms follow a typical Gumbel distribution. The DMC gives the choice probabilities as a function of observable variables based on the maximum utility principle, and thus the probability that ship i chooses route n is:

$$P_{ni} = \frac{\exp(V_{ni})}{\sum_{j=1}^{J} \exp(V_{nj})} \tag{2}$$

where V_{ni} and V_{nj} are defined by Eq. (1). The observable part of the disutility of each alternative is assumed to be the summation of the cost. Without loss of generality, we consider a voyage-based decision and use voyage-based data in the following analysis. Thus,

$$V_{ni} = -C_{total}$$
$$C_{total} = C_{charter} + C_{fuel} + Toll$$
$$C_{charter} = (T_{Nav} + T_{wait}) \times f_{charter}$$
$$C_{fuel} = C_{nav} + C_{wait}$$
$$C_{nav} = R_{nav} \times T_{nav} \times P_{fuel}$$
$$C_{wait} = T_{wait} \times R_{wait} \times P_{fuel}$$

where
C_{total} is the total cost;
C_{charter} is the charter fee;
C_{fuel} is the fuel cost;
$Toll$ is the Suez Canal toll;
P_{fuel} is the fuel price;
V_{nav} is the navigating velocity;
T_{nav} is the navigating time;
T_{wait} is the waiting time;
R_{wait} is the fuel consumption rate when the ship is waiting; and
R_{nav} is the fuel consumption rate when the ship is navigating, which is calculated as $R_{nav} = P \times G_0 \times \left(\frac{V_{nav}}{V_0}\right)^3$, in which P is the propulsion power, G_0 is the design fuel consumption rate, and V_0 is the design velocity.

The standard approach in probabilistic discrete choice models for incorporating qualitative variables is to use ordinal and/or dummy variables (Train, 2009). The variables and attributes considered are relevant to the route-choosing process and are significant determinants of the route choice for the present study, that is, actual expenses and the monetary value of time. The results of the DCM will allow the emissions from ships to be determined.

3.1. Parameter set

Without loss of generality, Singapore is selected as the port of origin and Rotterdam as the destination. For benchmarking, we consider the two alternative routes starting from Singapore and then passing through the Malacca Strait via either the Mediterranean Sea or the Cape of Good Hope. It is assumed that the Malacca Strait does not have any impact on shipping. The distance from Singapore to Rotterdam through the Mediterranean Sea is 9342 nautical miles, whereas it is 14,180 nautical miles via the Cape of Good Hope (Ports.com, 2016).

Container ships, tankers, and bulk carriers are the three largest groups of vessels within the merchant fleet, and therefore these market segments deserve the greatest attention. The amount of cargo shipped in containers has increased considerably over the last 19 years from about 50 million TEU (twenty-foot equivalent units) in 1996 to about 170 million TEU in 2014 (UNCTAD, 2014, Fig. 1.5a), resulting in a rapid increase in both the number and size of container ships during this period. Without loss of generality, this paper focuses on container ships.

3.2. Time value of ships

The total cost of running a ship includes the daily cost, the fuel fee, and canal tolls. It is well known that the constituent of the daily cost is quite complex. To simplify the numerical analysis, a time charter rate is applied to calculate the daily cost of a ship. Table 1 presents the average time charter rate in 2017 (January-June). The average cost per TEU reduces as ship size increases, as shown by a regression conducted to indicate the trend (Fig. 2).

Table 1
Time charter rates. *Data source:* VHSS (2017) New ConTex http://www.vhss.de/index.php?id=68&L=1.

Ship size (TEU)	Time charter rate ($/day)	Charter rate ($/day/TEU)
1100	6349	5.772
1700	6948	4.087
2500	7438	2.975
2700	7677	2.843
3500	7181	2.052
4250	6856	1.613

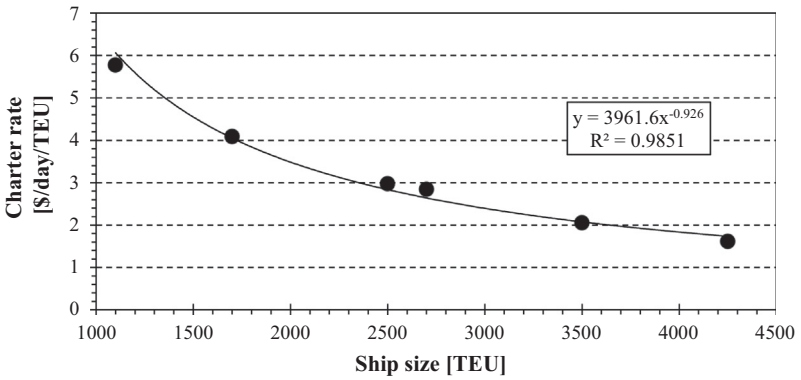

Fig. 2. The relationship between charter rate and ship size.

Table 2
Suez Canal tolls. *Data source:* Suez Canal Authority, http://www.suezcanal.gov.eg/tollcirculars.aspx.

Ship condition	Toll (SDR/SCNT)[a]						
	First 5000	Next 5000	Next 10,000	Next 20,000	Next 30,000	Next 50,000	All others
Laden	7.88	5.41	4.2	2.94	2.73	2.15	2.05
Ballast	6.7	4.6	3.57	2.5	2.32	1.83	1.74

– 4% for vessels carrying one tier
– 6% for vessels carrying two tiers
– 8% for vessels carrying three tiers
– 11% for vessels carrying four tiers
– 15% for vessels carrying five tiers
– 21% for vessels carrying six tiers
– An increase of 2% shall be applied for each tier in excess of six tiers, which means that a surcharge of 23% shall be applied on vessels carrying seven tiers of containers . . . etc.

[a] 1 SDR ≈ 1.38 USD, June 2017, https://www.imf.org/external/np/fin/data/rms_sdrv.aspx.

3.3. Canal toll

According to the Suez Canal Authority, the transit toll varies with ship type. There are 13 ship types in the Toll Circular. Table 2 lists the toll that container ships should pay according to their SCNT (Suez Canal Net Tonnage). Additionally, containerships have to pay a surcharge for the container tiers on deck.

SCNT (Suez Canal Net Tonnage) is the basis of all dues and charges to be paid. It is the net tonnage resulting from the system of measurement laid down by the International Commission held at Constantinople in 1873, and duly entered on the special certificates issued by the competent authorities in each country. It is difficult to use a model to illustrate the computation of the SCNT. As a consequence, the relationship between normal ship size and SCNT is found to calculate a ship's SCNT (Fig. 3).

3.4. Canal capacity and waiting time

Waiting time is closely related to the capacity of the Suez Canal. In calculating the maximum shipping capacity, the physical layout of the canal and its operating system must be taken into account.

According to the Suez Canal Rules of Navigation (Suez Canal Authority, 2015), three main convoy systems are applied in the canal:

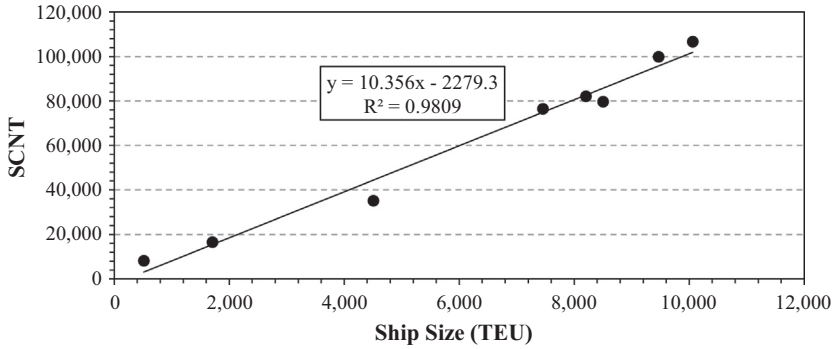

Fig. 3. The relationship between Suez Canal net tonnage (SCNT) and ship size.

- Northbound Convoy (N)
  This starts at 06:00 h. The Northbound Convoy has almost a free run from the Port of Suez until Port-Said.
- First Southbound Convoy (S_1)
  This starts from 00:00 to 05:00 h. This convoy has a free run to the Bitter Lakes, passes through the eastern branch of the Ballah by-pass, the eastern channel of Lake Timsah, the Deversoir West channel, and anchors in the Western Anchorages in the Bitter Lakes. The first ship of the northbound convoy may cross the last ship of the first southbound convoy at 102 km.
- Second Southbound Convoy (S_2)
  This starts from 07:00 to 09:00 h. Ships make fast in Ballah West Branch, and continue the route after the last northbound ship clears. The last ship of the northbound convoy may cross the last ship of the second southbound convoy at El-Ballah south (50 km).

To calculate the canal capacity, the following assumptions are made:

(1) The storage capacity of the Bitter Lakes (between North-Light 102 km and South-Light 122 km) is 50 ships for the first southbound convoy;
(2) The storage capacity of the Ballah by-pass (between 50 and 61 km) is 20 ships for the second southbound convoy;
(3) The transit speed limit is 11–16 km/h;
(4) The interval between ships in a convoy is 10 min;
(5) The ship transit time for the canal is less than 24 h; and
(6) The length of the ship is ignored.

To calculate the capacity of the Suez Canal, an optimal solution of the following programming needs to be identified:

$$\text{Maximize} \quad M = (N + S_1 + S_2) \tag{4a}$$
$$\text{Subject to :} \quad S > 0; \tag{4b}$$
$$0 \leqslant S_1 \leqslant 50; \tag{4c}$$
$$0 \leqslant S_2 \leqslant 20; \tag{4d}$$
$$11 \leqslant V_N \leqslant 16; \tag{4e}$$
$$11 \leqslant V_{S1} \leqslant 16; \tag{4f}$$
$$11 \leqslant V_{S2} \leqslant 16; \tag{4g}$$
$$\frac{102}{V_{S1}} + \frac{S_1}{6} - \left(\frac{60}{V_N} + 6\right) \leqslant 0; \tag{4h}$$
$$\frac{50}{V_{S2}} + \frac{S_2}{6} - \left(\frac{112}{V_N} - 1\right) \leqslant 0; \tag{4i}$$
$$\frac{60}{V_{S1}} + \frac{60}{V_N} + 6 + \frac{N}{6} \leqslant 24; \tag{4j}$$
$$\frac{112}{V_{S1}} + \frac{112}{V_N} - 1 + \frac{N}{6} \leqslant 24; \tag{4k}$$
$$\frac{162}{V_N} + \frac{N}{6} \leqslant 24; \tag{4l}$$

where

Table 3
Fuel parameters. *Data source:* Bunker Index (2017) http://www.bunkerindex.com/prices/bixfree.php?priceindex_id=5.

		HFO 380	MGO
G_0 (g/kWh)		170.00	170.00
Price ($/ton)[a]		347.5	602.7
Emission Factors[b]	CO_2	3.13	3.19
	SO_2	0.054	0.001

[a] The price is an average of prices from April 2017 to June 2017.
[b] *Data source:* IMO GHG Study (2009).

N, S_1, S_2 are the numbers of ships in the northbound convoy, first southbound convoy, and second southbound convoy, respectively;
M is the total daily ship traffic; and
V_N, V_{S1}, V_{S2} are the transit speeds of the ships in the Northbound Convoy, first Southbound Convoy, and second Southbound Convoy, respectively.

Eq. (4a) is the objective function to maximize the total daily ship traffic through the Suez Canal. Eq. (4b) defines the northbound traffic as positive. Eqs. (4c) and (4d) constrain the storage capacities to 50 ships and 20 ships for the first and second southbound convoys, respectively. Eqs. (4e)–(4g) constrain the transit speeds to be in the range of 11–16 km/h. Eq. (4h) defines that the first ship of the northbound convoy may cross the last ship of the first southbound convoy at 102 km. Similarly, Eq. (4i) defines that the last ship of the northbound convoy may cross the last ship of the second southbound convoy at 50 km. Eqs. (4j)–(4l) ensure that the transit time of ships is within 24 h.

The solution is $N = 61.52679$; $S_1 = 21.72321$; $S_2 = 20$; $V_{S1} = 16$; $V_{S2} = 16$; $V_N = 15.01676$. Thus, the capacity of the Suez Canal is (N=) 61 ships for the northbound convoy, (S_1=) 21 ships for the first southbound convoy, and (S_2=) 20 ships for the second southbound convoy. The Suez Canal Authority reported that the record high traffic in 2008 was 10,967 (northbound) and 10,448 (southbound) transits or 30.0 (northbound) and 28.5 (southbound) transits per day, and therefore the canal capacity determined by the nonlinear programming should be appropriate. Accordingly, for the ships sailing from Suez port to Port Said, if the number of ships is larger than 61, the ships arriving after the 61st ship have to wait for an extra 24 h. Thus, the waiting time of the j-th ship is:

$$T_{wait}^{j} = \begin{cases} \frac{j-1}{6}, & j \leqslant 61 \\ \left\lfloor \frac{j-1}{61} \right\rfloor \times 24 + \frac{(j-1) - \left\lfloor \frac{j-1}{61} \right\rfloor \times 61}{6}, & j > 61 \end{cases} \tag{5}$$

where j denotes the j-th ship, $\lfloor x \rfloor$ is the floor function (or greatest integer function) of x and gives the largest integer less than or equal to x.

3.5. Propulsion power and design speed

According to the data in the literature (MAN Diesel & Turbo, 2009), the regressions for power and design speed for different containership sizes are given in Fig. 3.

3.6. Fuel parameters

The fuel parameters that are used in this paper are listed in Table 3.

4. Results

4.1. Route choice

With the parameters described in Section 3, the relationship between the probability that a ship chooses the Suez Canal Route (P_{Suez}) and the waiting time T_{wait}^{j} are analysed based on the model. Let N_{Suez} denote the number of ships passing through the Malacca Strait before that choosing the route via the Mediterranean Sea. Fig. 4 shows that both the change in ship size and $N_{Arrival}$ affect P_{Suez}. The probability increases with ship size when the ship is below 15,000 TEU, and then reduces sharply. Jump-cluster phenomena exist in the probability curves when N_{Suez} is a multiple of 61 (because the capacity of the northbound convoy is 61 ships per day).

We also analyse the relationship between the Suez Canal toll and P_{suez}. P_{suez} declines as the toll is raised (Fig. 5). When the increase in the toll is less than 70% of the original toll, P_{suez} falls after a peak around the point corresponding to a ship size of 5000 TEU.

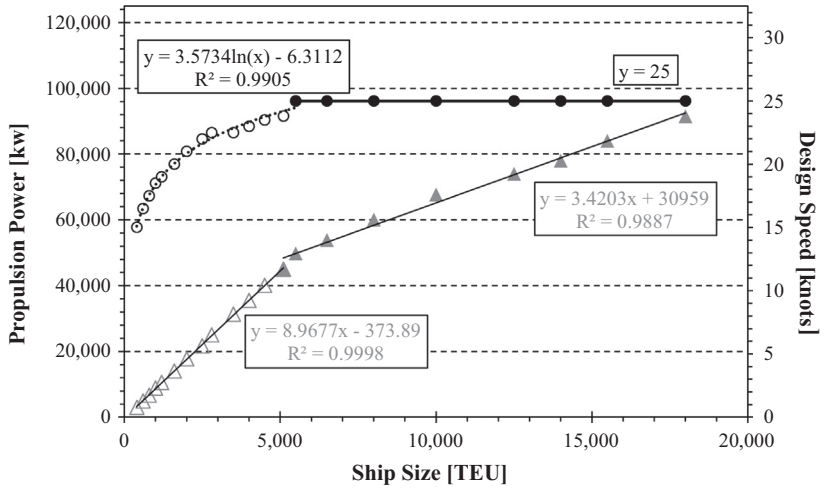

Fig. 4. The relationship between propulsion power, design speed and ship size. *Data source:* MAN Diesel & Turbo (2009).

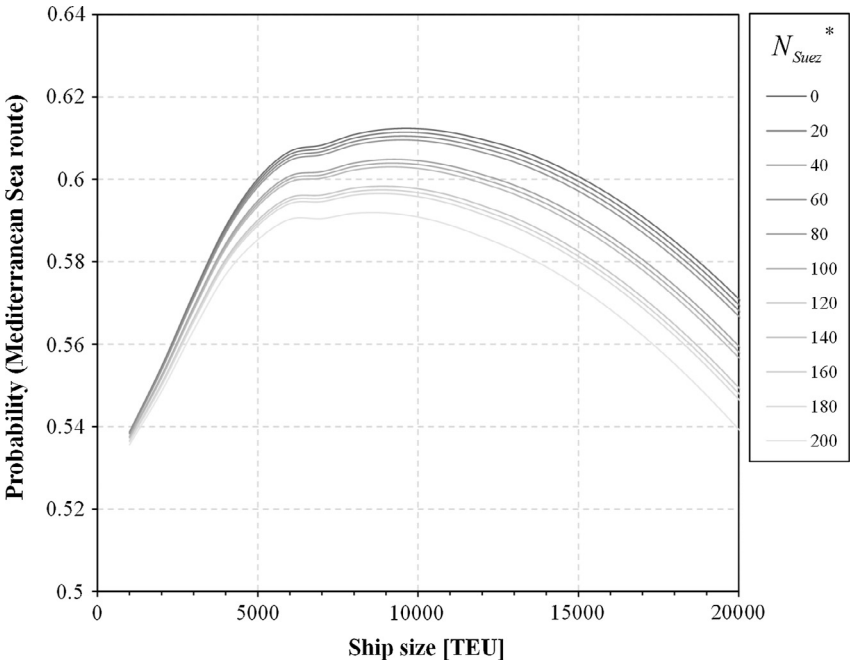

Fig. 5. The probability of choosing the Mediterranean Sea route with respect to ship size and different percentages of arrival northbound ships. *Suez N denotes the number of ships passing through the Malacca Strait before choosing the Mediterranean Sea route or the Cape of Good Hope route.

If the Mediterranean Sea is set as an ECA and the distance across the ECA is 2318 nautical miles, then how will this affect the route choice decision-making of Asia–Europe shipping? To investigate this effect, we assume that there are three alternatives for container ships: (1) Choose the Mediterranean Sea route and pay the ECA Regulation Surcharge; (2) choose the Mediterranean Sea route and use marine gas oil (MGO) instead of primarily heavy fuel oil (HFO) when transiting through the canal; and (3) choose the route via the Cape of Good Hope. Fig. 6 illustrates the results for the route choice of ships when the ECA Regulation Surcharge increases from 0% to 100% of the canal toll. As the ECA Regulation Surcharge becomes higher, fewer ships choose the Mediterranean Sea route. Large ships prefer to use the Cape of Good Hope route.

4.2. Ship emissions

With the route choice probability, CO_2 and SO_2 emissions are calculated according to the following function:

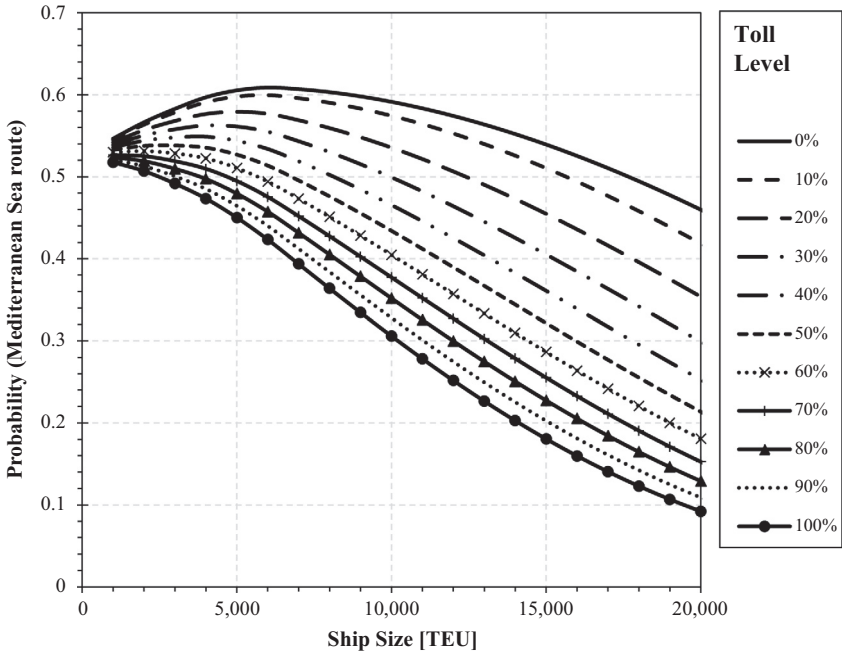

Fig. 6. The probability of choosing the Mediterranean Sea route with respect to ship size and different toll levels.

$$F = R_{nav} \times T_{nav} \tag{6a}$$

$$E = F \times e \tag{6b}$$

where

F is the fuel consumed;
E is the emission;
e is the emission factor of corresponding gas.

A change in route choice probability (the division of route choices) affects the local and regional emissions simultaneously. As a ship shifts from one route to the other, the emissions will be shifted from the original route to the alternative route. In the present case, if ECAs are established and ECA Regulation Surcharge is charged to ships passing the Mediterranean Sea, a portion of ships will change their routes from the Suez Canal to the Cape of Good Hope. Because the route via the Cape of Good Hope is longer than that via the Suez Canal, the total amount of ship emissions in the region may increase. Fig. 8 demonstrates the change in CO_2 and SO_2 emissions for the Suez Canal if the Mediterranean Sea ECA is to be established. Fig. 9 similarly demonstrates the change in CO_2 and SO_2 emissions for the Suez Canal and Cape of Good Hope routes. The increase in ECA Regulation Surcharge reduces shipping emissions in the Mediterranean Sea but has the opposite effect on the total emissions in the Mediterranean Sea and Good Hope routes. For the route passing the Mediterranean Sea, emissions of the two gases are reduced and the reduction increases with ship size up to 5000 TEU. As shown in Fig. 8, CO_2 emissions decrease remarkably for ship sizes up to 5000 TEU, whereas they further decrease, although moderately so, for larger ships. SO_2 emissions decrease, generally speaking. Local minima of CO_2 and SO_2 emission points are found for a ship size of around 5000 TEU.

To reduce ship emissions, the local government would set a high Surcharge rate or establish an ECA so as to restrict ship traffic to an appropriate level (Fig. 8). However, a decrease in the number of ship transits passing the Mediterranean Sea would raise those via the Cape of Good Hope and consequently raise the regional amount of emissions (Fig. 9). This is because ships are inclined to transit via the alternative, but longer, route with the absence of ECA Regulation Surcharge and other emission control measures. Most previous studies have considered the case of only single route. If control measures are applied to one of alternative routes only, the regional amount of emissions may be more than the minimum level.

The simulation results show that the scale economy (larger ship size) provides a very effective reduction in emissions for a ship size of up to 5000 TEU but the reduction becomes moderate for ships larger than 5000 TEU. In this case, it is necessary to use other measures to reduce CO_2 emissions from containerships. However, the establishment of ECAs will shift the emissions from Emission Control Areas to adjacent areas, and the overall amount of emissions is not necessarily reduced. An ECA

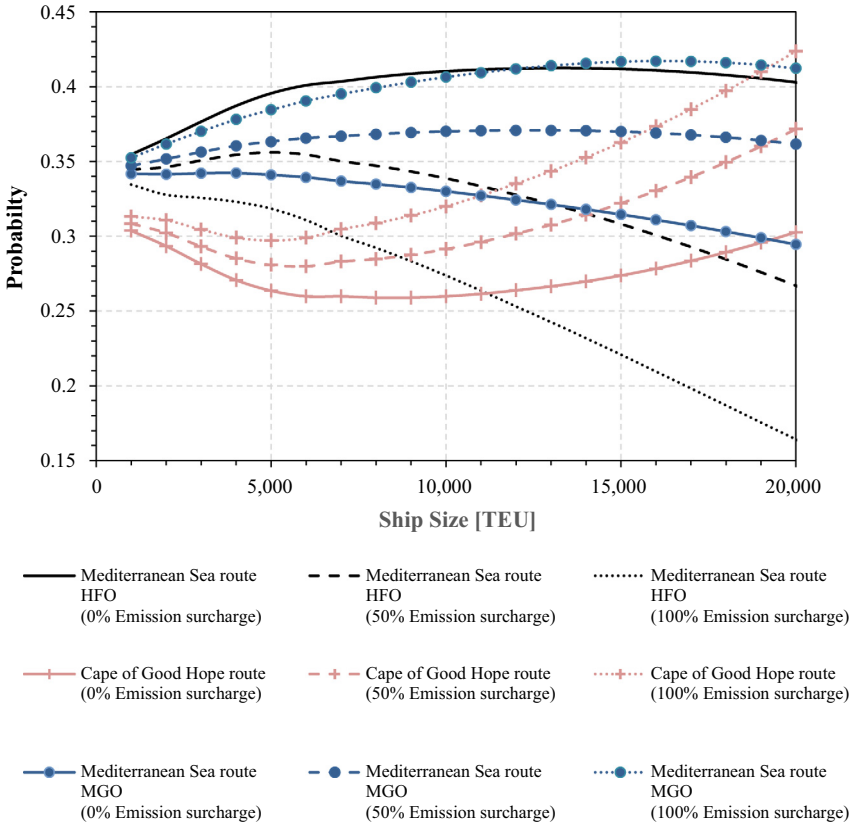

Fig. 7. Route choice in the presence of hypothesised Mediterranean Sea ECA.

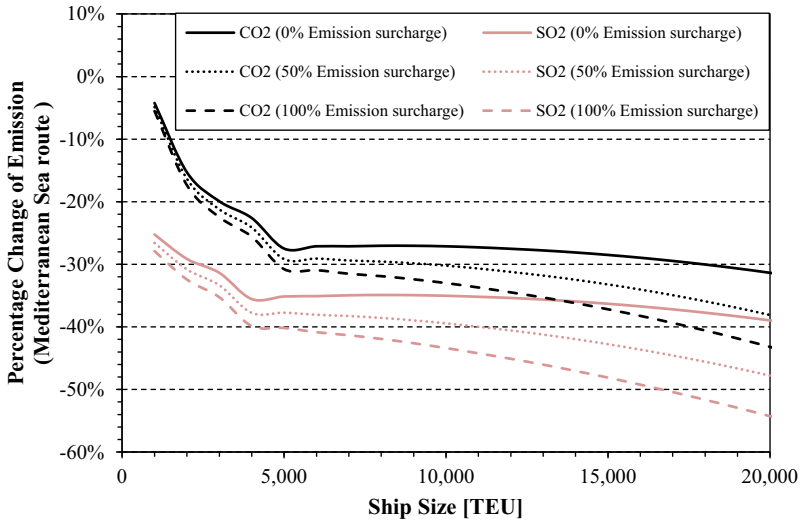

Fig. 8. Changes in CO_2, SO_2 emissions of Mediterranean Sea route.

Regulation Surcharge also has a weak impact on ship emissions. We conclude that further reduction in ship emissions will need to rely on technology advancement.

There are many options for ship emission control. Most of these options are available on a local basis, such as the establishment of an ECA Regulation Surcharge and an ECA. When an ECA Regulation Surcharge is introduced, the demand for ship transits declines. The amount of reduction in demand depends on the relative attractiveness of the original route against that

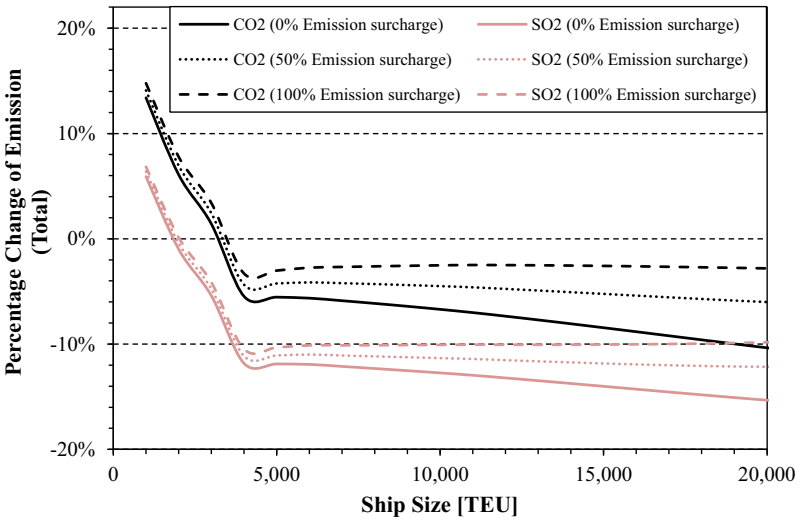

Fig. 9. Changes in CO2 and SO2 emissions for the Mediterranean Sea route and Cape of Good Hope route.

of the rival route as well as on the amount of ECA Regulation Surcharge introduced. It is noted from Figs. 7 and 8 that a moderate increase in emissions is observed from 5000 to 10,000 TEU. Our analysis illustrates the complexity of setting appropriate emission control measures. These environmental measures have regional-scale effects, and it is important to realise that ship emission reductions can be maximised when a regional perspective is considered.

The simulation is readily extended to analyse other effects, such as slow steaming. It should be noted that currently the steaming speeds of container ships are low. Further research is needed to study the heterogeneous effect of factors in the discrete choice model. The present study should also be extended in future work to consider route choice in networks of overlapping routes (Hoogendoorn-Lanser et al., 2005; Bovy, 2009). Both extensions will be important because any future framework for ECA management should be based on the adequate modelling of choice behaviour.

5. Conclusions

This paper develops a route choice model for Asia–Europe shipping by using the Discrete Choice Model. Route choice and shipping emissions are analysed to investigate the effect of hypothesised Mediterranean Sea ECA, using relationships between ship size and power, ship size and design speed, and ship size and Suez Canal net tonnage. Furthermore, the capacity of the Suez Canal is calculated using an optimization model to determine the waiting time pattern. The results demonstrate that the probability of ships choosing the route via the Mediterranean Sea increases with ship size for sizes of up to 5000 TEU, and then reduces sharply. The findings offer three implications, if an ECA is established. For the Mediterranean Sea under the hypothesised ECA, emissions of both CO_2 and SO_2 are reduced and the reduction increases with ship size up to a size of 5000 TEU. From the regional perspective, CO_2 and SO_2 emissions decrease with increasing ship size. Significant reductions will be observed for ship sizes of up to 5000 TEU, but only moderate reductions will be observed for ship sizes in excess of 5000 TEU. Therefore, the establishment of ECAs and ECA Regulation Surcharge will have considerable effects on small containerships but moderate impacts on containerships. This is because large containerships have been already environmentally friendly and re-routing cannot further reduce the regional ship emissions. More importantly, our study encourages the benefits of international coordinating approach between regions.

Although our investigation provides useful policy recommendations, the model used in this study may be extended to investigate other relevant issues for example the operational issues such as slow steaming, the non-linear emission-and-speed relationship. More in-depth studies are needed for the development of future international policies on ship emission issues.

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